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14. ABSTRACT
Acoustic tomography of the atmospheric surface layer (ASL) is based on the measurements of the travel times of sound propagation between speakers and microphone which constitute a tomography array. The travel times are then used as input parameters in the inverse algorithms for reconstruction of temperature and wind velocity fields. In this project, we have continued our long-term theoretical and experimental studies of acoustic tomography of the ASL. The inverse algorithms for the tomographic reconstruction were modified and extended. In particular, two

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Report Title

Final Report: Acoustic tomography of the atmospheric surface layer

ABSTRACT

Acoustic tomography of the atmospheric surface layer (ASL) is based on the measurements of the travel times of sound propagation between speakers and microphone which constitute a tomography array. The travel times are then used as input parameters in the inverse algorithms for reconstruction of temperature and wind velocity fields. In this project, we have continued our long-term theoretical and experimental studies of acoustic tomography of the ASL. The inverse algorithms for the tomographic reconstruction were modified and extended. In particular, two algorithms were developed for the assessment and elimination of the systematic errors in the travel-time measurements. The algorithms were applied for the reconstruction of the turbulence fields from the travel times obtained with the acoustic tomography array at the Boulder Atmospheric Observatory (BAO). The BAO tomography array was also used for measurements of the area-averaged values of temperature, wind velocity, and horizontal heat flux. To improve a spatial resolution of an ultrasonic anemometer, it was suggested that one consider it is as a small acoustic tomography array and apply appropriate inverse methods for reconstruction of temperature and velocity. The upgrades of the BAO acoustic tomography array were completed and new experiments were carried out.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
09/22/2013	7.00	Sergey N. Vecherin, Vladimir E. Ostashev, Christopher W. Fairall, D. Keith Wilson, Ludovic Bariteau. Sonic Anemometer as a Small Acoustic Tomography Array, Boundary-Layer Meteorology, (08 2013): 0. doi: 10.1007/s10546-013-9843-9
09/22/2013	8.00	Sergey N. Vecherin, Vladimir E. Ostashev, D. Keith Wilson. Assessment of systematic measurement errors for acoustic travel-time tomography of the atmosphere, The Journal of the Acoustical Society of America, (09 2013): 1802. doi: 10.1121/1.4816411

TOTAL: 2

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received		Paper
03/21/2012	3.00	S. N. Vecherin, V. E. Ostashev, D. K. Wilson, A. Grached. Utilization of an acoustic tomography array as a large sonic anemometer/thermometer, Proceedings of Meetings on Acoustics, (01 2012): 0. doi:

TOTAL: 1

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
06/12/2012	4.00	Vladimir Ostashev, Sergey Vecherin, Keith Wilson, Alfred Bedard, Jesse Leach, Kurt Clark, Christofer Fairall, Daniel Wolfe. Acoustic travel-time tomography of the atmosphere at the Boulder Atmospheric Observatory, 16th International Symposium for the Advancement of the Boundary-Layer Remote Sensing. 05-JUN-12, . : ,
07/21/2011	2.00	V. E. Ostashev, S. N. Vecherin, D. K. Wilson, C. W. Fairall. Recent Developments in Acoustic Tomography of the Atmosphere, 14th Long Range Sound Propagation Symposium. 17-MAR-11, . : ,

TOTAL: **2**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
11/07/2012	5.00	Sergey Vecherin, Vladimir Ostashev, D. Keith Wilson. Assessment of systematic errors in the tarvel times in acoustic tomography of the atmosphere, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA (11 2012)
12/03/2012	6.00	S. N. Vecherin, V. E. Ostashev, C. W. Fairall, D. K. Wilson, L. Bariteau. Sonic Anemometer as a Small Acoustic Tomography Array, Boundary-Layer Meteorology (12 2012)

TOTAL: **2**

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
V. E. Ostashev	0.29	
A. J. Bedard	0.04	
FTE Equivalent:	**0.33**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
D. Wolfe	0.10
D. Hazen	0.18
S. Vecherin	0.10
FTE Equivalent:	**0.38**
Total Number:	**3**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Theoretical and numerical studies of acoustic tomography of the atmospheric surface layer were performed in collaboration with Dr. D. K. Wilson of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). He is a coauthor in all publications supported by this project. This means a direct transfer of the results obtained for CRREL.

Final Progress Report

1. Statement of the problem

Acoustic tomography of the atmosphere is similar to that in medicine where ultrasound waves or x-rays probe a particular organ of a human body resulting in an 'image' of that organ. In the case of acoustic tomography of the atmospheric surface layer (ASL), the travel times of sound propagation between speakers and microphones of a tomography array are measured and used as input parameters for reconstruction of temperature and wind velocity fields. Improved knowledge about these fields is important in many applications such as boundary layer meteorology, theories of turbulence, experimental validation of large eddy simulation (LES), and studies of electromagnetic and acoustic wave propagation. Acoustic tomography has certain advantages in comparison with existing meteorological instrumentation and can also provide unique measurements (e.g., spatial temperature fields), which are not feasible with other methods.

Under previous ARO sponsorship, the array for acoustic tomography of the ASL was built at the Boulder Atmospheric Observatory (BAO) and related theoretical studies performed. The goals of the current project were twofold: (i) to continue theoretical and experimental studies of acoustic tomography of the ASL, and (ii) to upgrade the BAO acoustic tomography array.

2. Summary of the most important results

The inverse algorithms for reconstruction of the temperature and wind velocity fields in acoustic tomography of the ASL have been modified and extended. The algorithms were applied for reconstruction of the turbulence fields in the acoustic tomography experiments at the BAO. The BAO tomography array was also used for measurements of the area-averaged values of the temperature, wind velocity, and horizontal heat flux. To improve a spatial resolution of an ultrasonic (sonic) anemometer, it was suggested that one consider it is as a small acoustic tomography array and apply appropriate inverse methods for reconstruction of the temperature and velocity fields. The upgrades of the BAO acoustic tomography array have been completed. Specific research areas of the project are summarized in sections 2.1 to 2.5:

2.1. New acoustic tomography experiments at the BAO. The BAO acoustic tomography array was built in 2008 with ARO support. The array consisted of eight towers, each of height 9.1 m, located along the perimeter of a square with the side length 80 m. Speakers and microphones were installed on the towers at the height of about 8 m above the ground. Three towers carried speakers

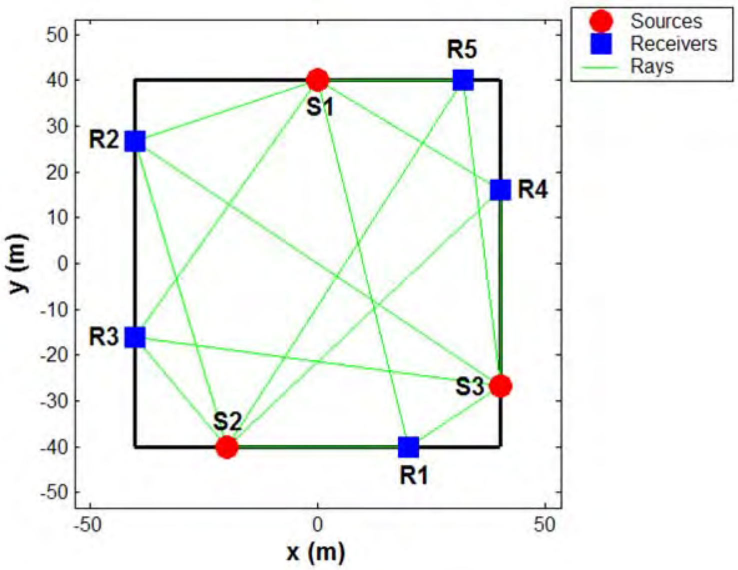

Figure 1: Location of eight towers of the 2008 BAO acoustic tomography array in a horizontal plane (x, y). Green lines indicate sound propagation paths from three speakers (red circles) to five microphones (blue squares).

and five towers had microphones. Figure 1 shows a schematic of the tomography array in a horizontal plane (x, y). Green solid lines are 15 sound propagation paths from the speakers to microphones. This experimental setup enabled us to perform 2D, horizontal-slice tomography. The speakers and microphones were connected via underground cables with the BAO Visitor Center, a small modular building located about 50 m from the array. A central command and data acquisition computer and other equipment of the acoustic tomography array were located inside the Visitor Center.

One of the goals of the current project was to upgrade the 2008 BAO tomography array (section 2.5). Prior to making significant modifications in the tomography array, several acoustic tomography experiments had been carried out [3]. Here, we describe one of such experiments conducted on July 2, 2012. To process the experimental data, numerical algorithms for calculations of the travel times of sound propagation between the speakers and microphones and subsequent reconstruction of the turbulence fields were revisited and improved. Figure 2 shows the reconstructed fields, which correspond to the time 14:41:30 of the experiment. Several 'cold' and 'warm' temperature eddies are clearly seen in the upper left plot. Other plots depict 'slow' and 'fast' eddies in the horizontal components of the wind velocity and its magnitude.

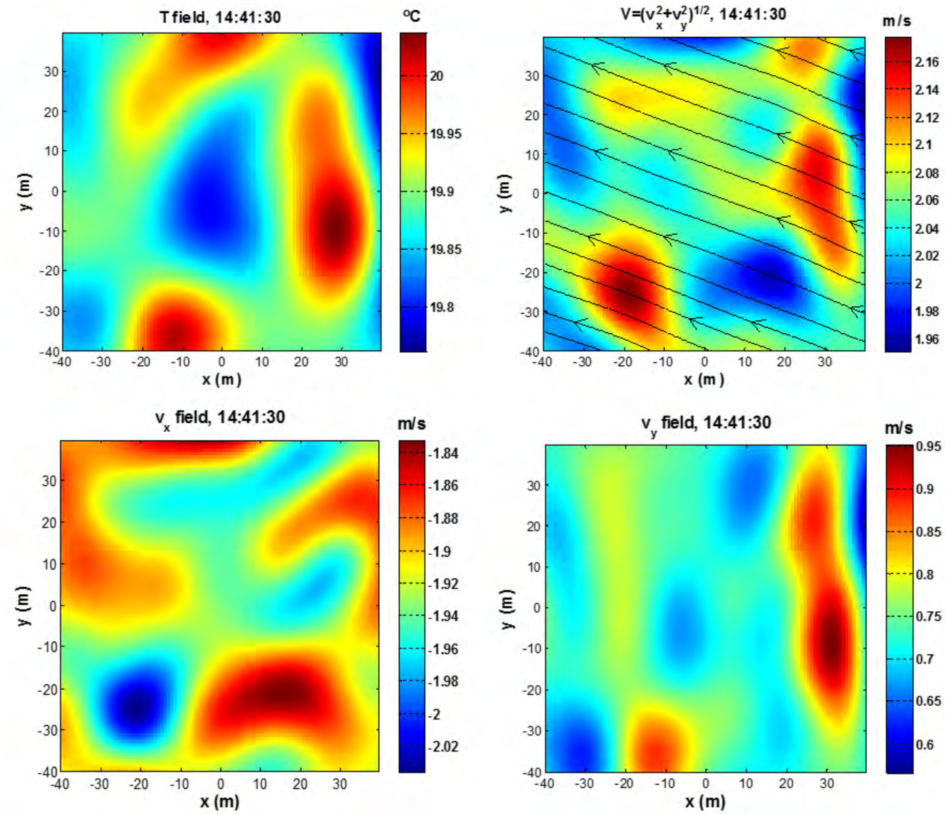

Figure 2: Temperature, magnitude and two horizontal components of the wind velocity obtained with the BAO acoustic tomography array on July 2, 2012. Arrows indicate the direction of the wind velocity.

2.2. Assessment of the systematic errors in acoustic tomography of the ASL. The assessment and elimination of the systematic errors in the measurements of the travel times of sound propagation between speakers and microphones which constitute a tomography array is crucial for accurate reconstruction of the turbulence fields. The systematic errors can be caused by several factors. First, there are errors in measurements of the time delays in hardware and electronic circuits of a tomography array and in synchronization of the transmitted and recorded signals. Second, the coordinates of speakers and microphones are known with some errors which can be recalculated into the travel-time errors. Third, a speaker is an extended source and its effective point of emission might be different in different azimuthal directions. There might be also other sources of the systematic errors, which despite all efforts for their elimination can still be present in experimental data. They

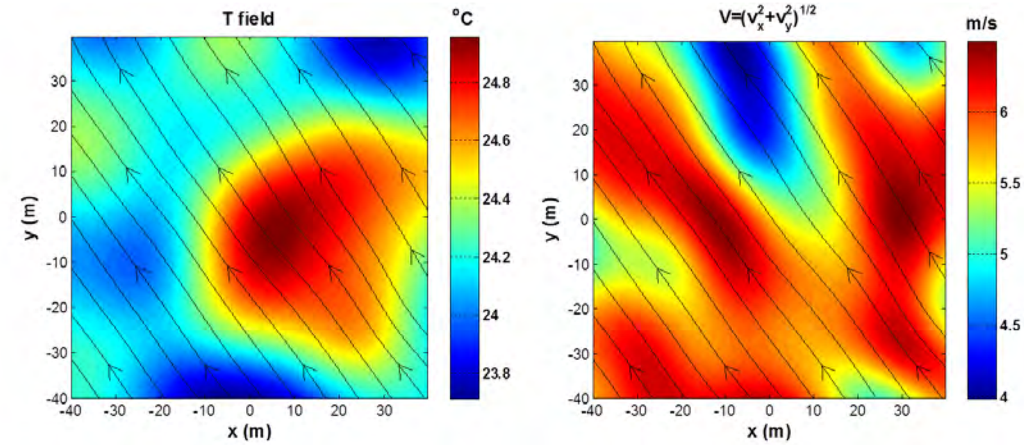

Figure 3: Reconstruction of the turbulence fields in the acoustic tomography experiment at the BAO on August 11, 2008. (Left) Temperature field. (Right) Magnitude of the wind velocity. Arrows indicate the direction of the wind velocity.

can slowly change in time due to changing conditions in electronic circuits, hardware, and the positions of transducers. The systematic errors in the travel-time measurements and related calibration of acoustic tomography arrays are probably the main reasons preventing this technique to become widely available to the general scientific community.

Two algorithms were developed [1] to mitigate the systematic errors in the travel-time measurements. The first algorithm aims at assessing and eliminating the errors during the reconstruction of the mean values of the temperature and wind velocity inside the tomographic area. The second algorithm uses the results of the first algorithm to identify the sound paths with the systematic errors and then eliminates these errors.

The two algorithms were tested in numerical simulations of the 2008 BAO acoustic tomography array. The turbulence fields were modelled using LES. The numerical simulations showed that the first algorithm can improve the temperature and velocity reconstruction when relatively small systematic errors are present in all sound propagation paths. The second algorithm significantly improves the reconstruction when systematic errors are present in a few, but not all, propagation paths.

The algorithms developed were also applied to the experimental data obtained on August 11, 2008 at the BAO. The systematic errors might have been caused by the errors in the transducer's coordinates that were not properly known at the time of the experiment. Without the algorithms developed, the expected errors in the reconstruction of the temperature and velocity fields were large.

By employing these algorithms, the expected errors were significantly reduced. The left plot in Fig. 3 shows the reconstructed temperature field. The expected error in reconstruction is about 0.22 K. Arrows indicate the direction of the wind velocity. The magnitude of the wind velocity is depicted in the right plot in Fig. 3. The expected error of reconstruction is 0.26 m/s. These expected error levels permit valuable data to be obtained. In Fig. 3, the cold and warm temperature eddies and slow and fast velocity eddies are reliably resolved since the temperature and velocity differences between them are larger than the reconstruction errors. The temperature and wind velocity fields were also obtained for other moments of the experiments. The resulting spatial fields were combined into 'movies', which show the temporal evolution of the turbulence fields.

2.3. Utilization of the BAO tomography array as a large sonic anemometer. A new approach for remote sensing of the area-averaged temperature, wind velocity, and horizontal and vertical heat fluxes with the BAO acoustic tomography array was suggested [4, 5, 6]. In this approach, the travel times of sound propagation between the speakers and microphones are measured repeatedly. Then, the area-averaged instantaneous values of temperature and velocity are reconstructed using the least-squares solution of the inverse problem. Using the time series of these values, the area-averaged horizontal heat flux is calculated. The area-averaged vertical flux might be inferred from the horizontal heat flux. This approach is similar to employing the acoustic tomography array as a large sonic anemometer. The feasibility of this approach was studied numerically and experimentally.

In numerical studies, the temperature and wind velocity fields inside the tomographic area were modeled with LES. A comprehensive numerical analysis of the LES fields revealed a spatial variation of the time-averaged temperature and wind velocity fields, and a significant spatial variation of the vertical and horizontal heat fluxes. These results clearly indicate the importance of the area-averaged measurements of these meteorological parameters. It was also shown that the area-averaged values of the temperature and wind velocity, their fluctuations, and horizontal heat flux corresponding to the LES fields agree with those reconstructed in the numerical simulations.

The acoustic tomography experiments in remote sensing of the area-averaged temperature, velocity, and horizontal heat flux were conducted at the BAO. Figure 4 depicts the temporal evolution of the area-averaged temperature and two horizontal components of the wind velocity obtained with the 2008 BAO acoustic tomography array on November 4, 2010. These data were then used to reconstruct the temporal evolution of the horizontal heat flux. The experiments demonstrated that acoustic remote sensing of the area-averaged values of the meteorological parameters is feasible.

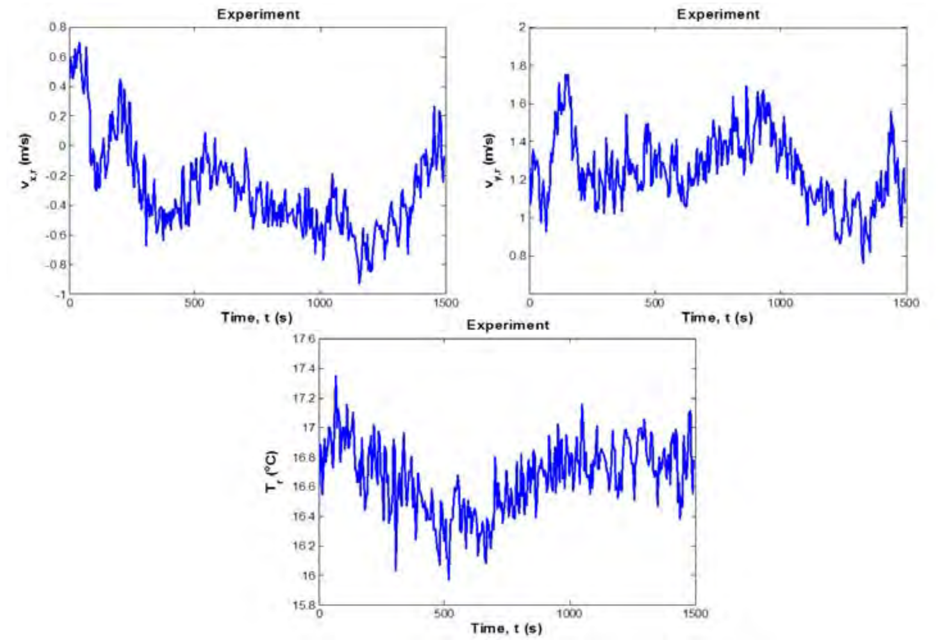

Figure 4: Temporal evolution of the area-averaged temperature and two horizontal components of the wind velocity obtained with the 2008 BAO tomography array on November 4, 2010.

2.4. Sonic anemometer as a small acoustic tomography array. Sonic anemometers are widely used for measurements of temperature and velocity. The spatial resolution of such anemometers is limited by the distance between their transducers. For many important applications such as studies of small-scale turbulence and turbulence closure models, it is desirable to increase this spatial resolution. We suggested [2, 5] to improve the spatial resolution by treating the sonic anemometer as a small acoustic tomography array and applying appropriate inverse algorithms for reconstruction of the temperature and velocity fields. A particular modification of the sonic anemometer was considered when the number of its transducers is doubled and the time-dependent stochastic inversion (TDSI) algorithm is used for reconstruction. Numerical simulations of the sonic anemometer and its suggested modification were implemented with the temperature and velocity fields modeled as quasi-wavelets. The simulations showed that the sonic anemometer enables measurements of the time series of temperature and velocity with relatively small root-mean square errors (RMSEs). The suggested modification of the sonic anemometer enables even more accurate measurements, especially for temperature and the vertical component of velocity, when the corresponding RMSEs are smaller than those for the sonic anemometer by factors 0.75 and 0.62, respectively.

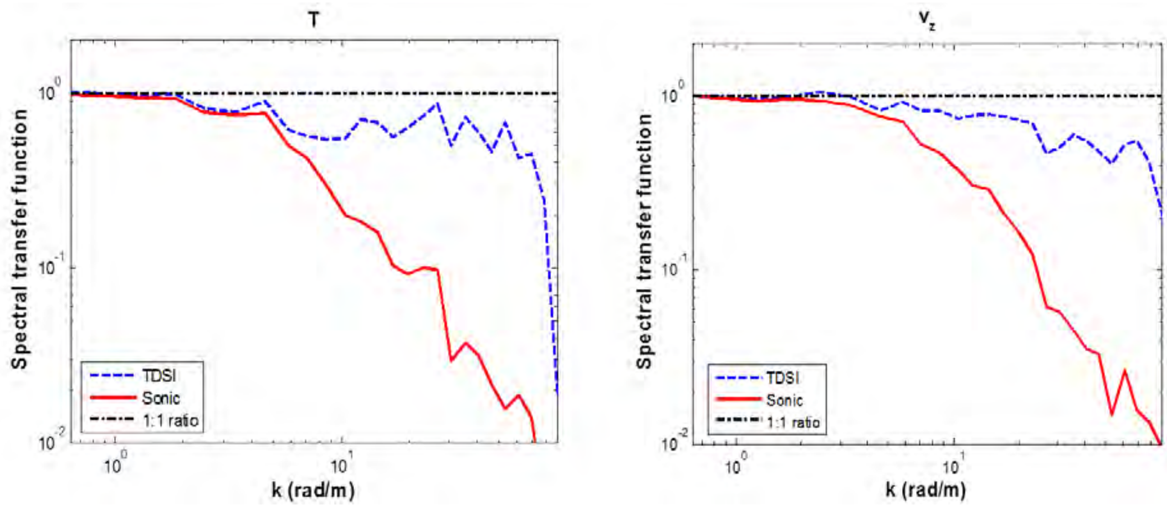

Figure 5: Spectral transfer functions obtained in numerical simulations of the sonic anemometer (solid red lines) and its suggested modification (dashed blue lines). The black, horizontal lines correspond to the case of perfect reconstruction. (Left) Temperature fluctuations. (Right) fluctuations in the vertical velocity.

Another advantage of the considered modification of the sonic anemometer is a significant increase in the spatial resolution of the spectra of temperature and vertical velocity fluctuations. In the numerical simulations, the spectral transfer functions were calculated. The temperature spectral transfer function is defined as the normalized cross-correlation between the temperature fluctuations in the quasi-wavelet field and those reconstructed in numerical simulations of the sonic anemometer or its suggested modification. The spectral transfer functions for three components of velocity fluctuations are defined similarly. For a perfect reconstruction of the fluctuations, the spectral transfer functions are equal to 1 and are shown in Fig. 5 as dash-dotted black lines. The horizontal axis corresponds to the turbulence wavenumber k. The spectral transfer functions obtained in the numerical simulations of a sonic anemometer and its suggested modification are shown as solid red and dashed blue lines. The left and right plots in Fig. 5 correspond to reconstruction of the temperature and vertical velocity fluctuations, respectively. It follows from these plots that the sonic anemometer enables the correct reconstruction of both the temperature and vertical velocity spectra for the wavenumbers k smaller than about 5 m^{-1}, while the suggested modification of the sonic anemometer allows us to do that for $k \lesssim 50$ m^{-1}. Thus, the sonic anemometer as a small tomography array increases the spatial resolution by a factor of 10. There is a preliminary agreement with the Applied Technologies Inc. (Longmont,

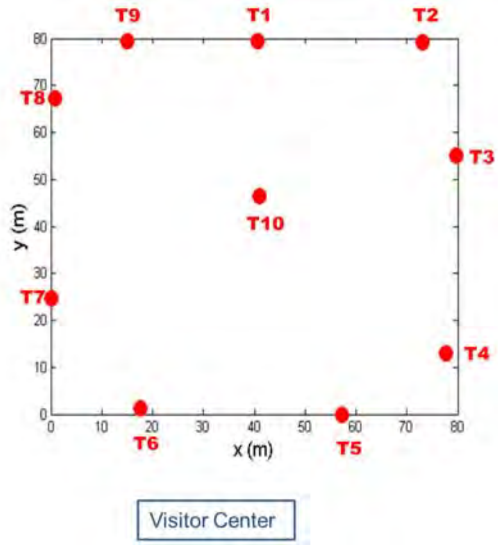

Figure 6: Schematic of the upgraded BAO acoustic tomography array in the horizontal plane (x, y). T1, T2, ..., T8 are towers of the 2008 tomography array; T9 and T10 are new towers. Also shown is the Visitor Center (not in scale).

CO) to develop a concept and build a commercial prototype of a sonic anemometer with improved spatial resolution.

2.5. Upgrades of the BAO acoustic tomography array. The upgrades of the BAO acoustic tomography array have been completed and the array became fully operational. Funds for the new components of the tomography array were provided by the DURIP grant [7].

Foundations for two new towers were built and the towers were assembled. Location of old (T1, T2, ..., T8) and new (T9, T10) towers of the tomography array is shown in Fig. 6. The underground conduits were laid to connect the new towers with the BAO Visitor Center, also shown in the figure. Tower T10 carries a sonic anemometer and thermometer probe for measurements of the temperature and wind velocity in the middle of the tomography array. Tower T9 is a 'spare' tower, where additional speaker, microphone, sonic anemometer, and/or thermometer probe can be installed or moved from other towers (e.g., if one them will break-down or for testing different locations of transducers and instruments). We also plan to use this tower in the new ARO proposal [8].

Both a speaker and microphone were installed on each of towers T1, T2, ..., T8. (In the 2008 BAO tomography array, these towers carried either a speaker or a microphone, see Fig. 1.) Installing of

Figure 7: Tower 5 of the upgraded BAO acoustic tomography array. A building behind the tower is the Visitor Center

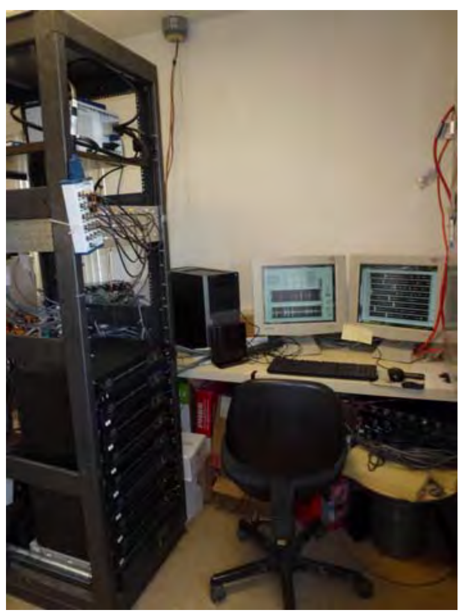

Figure 8: Acoustic tomography operation center inside the Visitor Center. The central command and data acquisition computer is on the desk. The rack on the left holds (from top to bottom) A/D interfaces, microphone filters, and eight speaker amplifiers.

new speakers and microphones required pulling out the existing cables from the underground conduits connecting the towers with the Visitor Center. Then, new cables were pulled in through these conduits. Where this process was not successful or feasible, new underground conduits were laid. New ruggedized microphone preamplifiers were purchased and placed in the instrumentation boxes attached to the towers at the height of about 2 m. Figure 7 depicts tower 5; a building behind the tower is the Visitor Center. New horns were purchased and mounted for all eight speakers. The horns have wider radiation patterns than the previous ones which enables to insonify more efficiently all microphones of the tomography array. Additional amplifiers for new speakers were placed inside the Visitor Center. Filters were built for eight microphone channels. A more powerful central command and data acquisition computer was acquired and integrated with other instrumentation. New A/D cards were purchased which enable transmission and recording of eight acoustic signals with synchronization of about a few microseconds (the accuracy required in acoustic tomography of the ASL). Significant efforts were devoted to make sure that the new components of the BAO acoustic tomography array are compatible with each other and already existing instrumentation. Figure 8 depicts the acoustic tomography operation center with the new equipment.

New signal forms were designed which enable more accurate determination of the travel times of sound propagation between speakers and microphones. Transmission/reception schedule was modified to identify signals transmitted by different speakers and recorded by a particular microphone. Software was developed to run acoustic tomography experiments from the central command and data acquisition computer and store the data on the computer. The data also include simultaneous measurements of the temperature and wind velocity with the sonic anemometer and temperature probe on tower 10. The coordinates of speakers, microphones, sonic anemometer, and temperature probe were measured. The time delays in the tomography array were carefully estimated for every speaker-microphone pair. Thorough testing was done to eliminate all drawbacks in the hardware and electrical circuits of the tomography array.

The upgraded BAO acoustic tomography array surpasses significantly the 2008 tomography array. The number of sound propagation paths is now 58, while previously it was 15. This increase provides more data for tomographic reconstruction of the turbulence fields. The upgraded tomography array enables reciprocal acoustic transmission, which might be advantageous for some tasks. The synchronization of the transmitted and recorded acoustic signals is now more accurate. The new microphone preamplifiers cause minimum distortion of acoustic signals, reduce the time delays, and are ruggedized. The sonic anemometer and temperature probe provide the temperature and wind

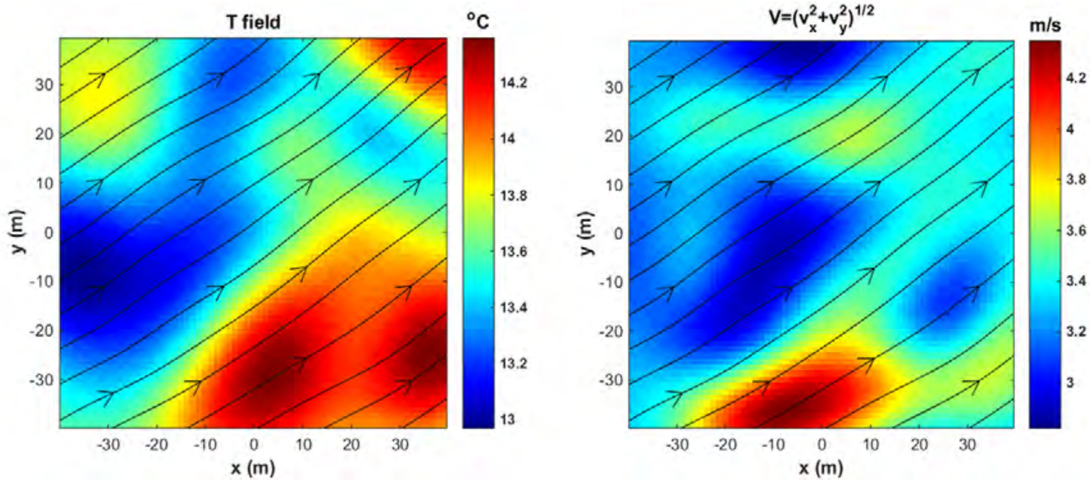

Figure 9: Temperature and magnitude of the wind velocity fields obtained with the upgraded BAO acoustic tomography array on November 9, 2014. Arrows indicate the direction of the wind velocity.

velocity in the middle of the tomography array. The upgraded tomography array has been used in several experiments. Figure 9 shows the temperature and the magnitude of the wind velocity fields obtained with the tomography array shortly after sunrise on November 9, 2014.

3. Publications supported under this grant

The results obtained in accomplishment of this project were published in two per-reviewed papers [1, 2] and four conference papers and abstracts [3]-[6].

References

[1] S. N. Vecherin, V. E. Ostashev, and D. K. Wilson, "Assessment of systematic errors in acoustic tomography of the atmosphere", J. Acoust. Soc. Am. **134** (3), 1802-1813 (2013).

[2] S. N. Vecherin, V. E. Ostashev, D. K. Wilson, C. W. Fairall, and L. Bariteau, "Sonic anemometer as a small acoustic tomography array", Boundary-Layer Meteorol. **149** (2), 165-178 (2013). DOI: 10.1007/s10546-013-9843-9.

[3] V. E. Ostashev, S. N. Vecherin, D. K. Wilson, A. J. Bedard, J. Leach, K. Clark, C. W. Fairall, and D. Wolfe, "Acoustic travel-time tomography of the atmosphere at the Boulder Atmospheric Observatory", Proc. ISARS 2012, Boulder, CO (2012).

[4] S. N. Vecherin, V. E. Ostashev, D. K. Wilson, and A. Grachev, "Utilization of an acoustic tomography array as a large sonic anemometer/thermometer", Proceedings of Meetings on Acoustics **14**, 045003 (2012).

[5] V. E. Ostashev, S. N. Vecherin, D. K. Wilson, and C. Fairall, "Recent developments in acoustic tomography of the atmosphere", Proc. 14th Intern. Symp. on Long Range Sound Propagation, Annapolis, MD, March 17-18, (2011).

[6] S. N. Vecherin, V. E. Ostashev, and D. K. Wilson, "Utilization of an acoustic tomography array as a large sonic anemometer/thermometer", J. Acoust. Soc. Am. **130**, No 4, Pt. 2, p. 2514 (2011).

[7] ARO Grant W9l INF-09-l-0234 (DURIP) "Acoustic tomography of the atmosphere at the Boulder Atmospheric Observatory". PIs: V. E. Ostashev and A. J. Bedard (2009).

[8] ARO proposal "Experimental validation of modern theories of sound propagation in a turbulent atmosphere". PIs A. J. Bedard and V. E. Ostashev (2014).